

Article

Additive Manufacturing as a Cost-Effective Solution for Stepped-Septum Polarizers

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Abstract

Additive manufacturing (AM) offers significant potential for producing complex, cost-effective, and high-performance components in the radio frequency and microwave industry. To significantly benefit from the manufacturing and design freedoms AM offers, AM-based microwave research must shift toward creating designs inherently optimized for AM. This study investigates various AM methods and materials for fabricating a polarizer operating in the K-band, a device widely used in microwave systems and well-suited for AM due to its intricate geometry. Four manufacturing approaches—machining and electroforming, stereolithography and electroless plating, bound metal deposition, and selective laser melting—were evaluated for accuracy, surface quality, and electrical performance. The polarizers were characterized through both single and back-to-back measurements and compared against CST Studio Suite simulations. To better understand discrepancies in performance, further analysis of material properties was conducted using conductivity measurements, skin depth calculations, optical microscopy, and scanning electron microscopy imaging. The results demonstrate that AM techniques can achieve good agreement with simulations and reveal the strengths and limitations of each method, guiding the selection of suitable AM processes for reliable and precise microwave component fabrication in the K-band.



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1. Introduction

Additive manufacturing (AM) has become an important tool for producing complex, lightweight, and cost-effective components across a range of industries. AM offers unique benefits by facilitating the fabrication of intricate metallic structures that are difficult to achieve with traditional methods [1]. Metal-based processes such as powder bed fusion (PBF) and directed energy deposition (DED) allow for the design flexibility and precision required to meet the demands of modern RF systems [2–4].

Although some commercial AM solutions provide high performance results, they are often expensive and based on proprietary technologies, limiting their practicality for largescale uses—such as antenna arrays requiring hundreds of identical parts [5,6]. Traditional subtractive manufacturing processes will always be limited in the geometries that can be achieved. With the demand for efficient, compact, and scalable systems growing, so too does the need for manufacturing techniques that can support both design complexity and production volume [6].

The current literature demonstrates the potential of AM for creating passive microwave components, such as waveguides, filters, and polarizers, entirely from metallic alloys, as discussed in [7–10]. These approaches not only support the necessary structural and electrical properties but also allow for design innovations that enhance electromagnetic (EM) performance. However, challenges such as surface roughness and difficulties in post-processing, especially for high-frequency applications, remain. Ongoing developments in printing resolution and surface finishing continue to address these issues, paving the way for broader integration of AM in microwave engineering [3,10–12].

A key limitation in current AM-based microwave component research lies in the lack of designs that fully leverage the capabilities of AM itself. As pointed out in [7], much of the existing literature focuses on conventional microwave designs with only minor modifications for AM compatibility. To truly benefit from AM's distinct manufacturing freedoms, the field must shift toward creating designs that are inherently optimized for additive processes, rather than restricting designs to common geometries [7].

Researchers have begun to steer towards this through the design of monolithic devices. With direct metal laser sintering (DMLS) and stereolithography (SLA) techniques, the authors of [12–14] were able to effectively manufacture monolithic devices combining septum polarizers and horn antennas. This not only successfully reduced the mass of these components, but their performance was also comparable to traditionally manufactured devices. However, surface roughness and shrinkage still impact performance with these printing methods. As such, although there are observable successes in this area of AM and RF/microwave devices, there is still room for improvement when it comes to the precision of delicate features.

Therefore, an investigation into the various types of manufacturing processes that are both cost-effective and precise for a device operating within the K-band will be useful for furthering AM's position within the RF/microwave industry.

Our work expands on this by investigating different AM methods and materials to compare with highly specialized AM processes and aims to identify a less expensive process that still produces an accurate microwave device.

Extensive reviews on AM—covering its history, materials, fabrication methods, technological trends, developments, and diverse applications—have been presented in several previous studies [8,15–17]. However, these works do not specifically focus on AM techniques for RF components. There is some research specifically focusing on AM for RF waveguide components, with extensive surveys on microwave-guided components fabricated using AM processes. However, these studies do not provide in-depth comparisons of the same components fabricated using multiple methods [18]. Some research efforts have examined AM within the RF and microwave domain, typically focusing on a single manufacturing method and investigating its influence on the design and performance of selected components. For instance, in [19], sinuous waveguides, filters, couplers, and combiners were fabricated using selective laser melting (SLM), and their simulated and measured results were compared for aluminum and titanium materials to assess the effects of surface roughness and electrical conductivity on component performance. A study [20] demonstrated the feasibility of using AM for a K-band filter, comparing a couple of AM processes and materials. However, its focus was largely on validating device functionality, with minimal analysis of material and surface effects [20]. To the best of the authors' knowledge, no prior study has conducted a comparative investigation of multiple AM techniques by fabricating the same microwave component using different methods and systematically evaluating the impact of each on performance. The present work offers a more comprehensive comparison across four fabrication methods—conventional (machining and electroforming) and advanced AM techniques (hybrid AM with coating, bound metal

deposition (BMD), and SLM). It further incorporates detailed material characterization, including conductivity, skin depth, and surface analyses, to directly link physical properties with RF performance. This broader approach provides deeper insight into how manufacturing methods influence component behavior and serves as a practical guide for selecting optimal AM techniques for RF and microwave applications.

Due to polarizers being widely used devices within the microwave industry, alongside the complex geometry of the device displayed in Figure 1, this polarizer design is a suitable candidate for AM methods.

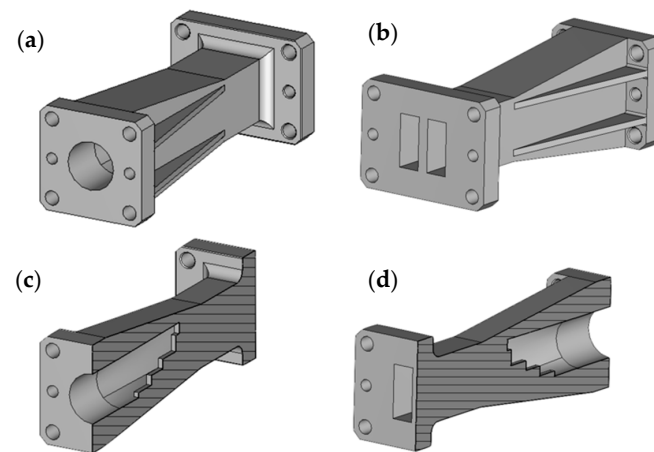


Figure 1. Polarizer internal and external design: (a) view of circular waveguide port, (b) view of rectangular waveguide ports, (c) internal view of stepped septum from circular port, (d) and internal view of stepped septum from rectangular port.

The septum polarizer design initially introduced in [21] exemplifies the notion of designing devices for AM (Figure 1). It was devised to produce a compact device for use in a K-band feed system by combining the stepped septum and a transition from circular to rectangular waveguides, allowing the device's overall length to be reduced [21]. The polarizer was designed to be 100 mm long to incorporate an off-the-shelf ferrite wedge load in the unused rectangular waveguide port. When not using a ferrite load, the overall length of the polarizer can be shortened to 60 mm, as shown in Figure 2, with no impact on the performance of the polarizer simply by shortening the rectangular waveguide sections before the stepped septum. The septum dimensions are identical for polarizers of both lengths and so these will be compared here to enable a comparison of the various manufacturing methods.

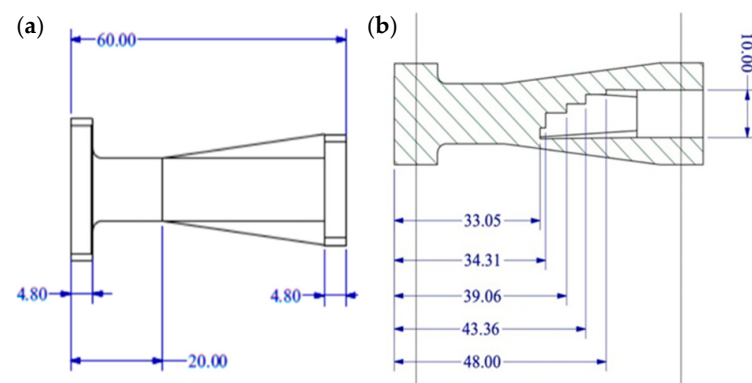


Figure 2. Polarizer side view with rectangular ports on the left and circular port on the right, with dimensions in millimeters (mm): (a) external dimensions of 60 mm length polarizer, (b) and dimensions of internal stepped septum.

This polarizer was chosen as its design of the combined stepped septum and circular to rectangular transition prohibited it from being manufactured with traditional subtractive methods. The high operation frequency of 20 GHz also meant that the design was small enough to be efficiently additively manufactured.

This paper is organized as follows: Section 2 summarizes the polarizer design and outlines the manufacturing processes used to produce these polarizers for testing. Section 3 compares the simulated and measured results obtained from each of these additively manufactured polarizers. Section 4 discusses the analysis of the printed material properties through conductivity measurements, skin depth calculations, microscopy, and scanning electron microscopy. Finally, Section 5 summarizes the conclusions drawn for the efficacy of different AM processes for producing a reliable and accurate polarizer for use in the K-band.

2. Polarizer Design and Manufacture

The polarizer used for this comparison is based on the design in [21] of a septum waveguide polarizer, with the length shortened to 60 mm. This design is excellent for AM due to the circular-to-rectangular waveguide transition and septum combination. The polarizer was designed using CST Studio Suite in the frequency domain [22]. It consists of a circular-to-square waveguide tapered transition with a septum introduced to perform the transformation from linear to circular polarization and to split the square waveguide into two rectangular waveguides. This version of the septum polarizer is particularly suited for additive manufacturing as the circular-to-square waveguide transition and septum have been optimized together to enable the length of the polarizer to be shortened. This makes machining or traditional subtractive manufacturing impossible.

As Figure 2 shows, the circular waveguide aperture has a diameter of 10 mm, and the rectangular waveguide ports are standard WR42 ports.

The polarizer was manufactured using four different methods by four different manufacturers: electroforming by Terahertz [23]; SLA and electroless plating by Swissto12 [24]; bound metal deposition (BMD) with a copper alloy by Australian National Fabrication Facility at the University of South Australia (ANFF UniSA) [25]; and selective laser melting, a powder-bed fusion technique by Northern Waves (NW) [26]. Of the four methods evaluated, the electroformed polarizers were the highest cost and this method does not lend itself to cost reduction. The cost of the SLA polymer polarizers was similar to that of the electroformed; however, this method lends itself to cost reduction by printing many devices simultaneously. The BMD and SLM had a similar cost per device and were an order of magnitude less expensive than the electroformed and SLA polarizers. The three printing methods all have similar production times; however, the electroforming process has much longer production times due to the more complex process. The following sections detail the methods, and the specific challenges associated with each.

2.1. Electroforming

The initial manufacture of this device was carried out by Terahertz using an electroforming process [23]. This electroformed polarizer (AM EF 100 mm) was manufactured at the original design length of 100 mm. The stepped septum was first machined in copper, along with an aluminum mandrel which formed the inverse of the rest of the polarizer. These were gold plated, combined, then placed into a copper solution bath for the growth phase. This electroforming process uses the copper solution and electrolysis to deposit copper onto the mandrel to form the polarizer. Once the copper growth phase was completed, the flanges were also machined and attached to each end of the polarizer through

soft soldering, as shown in Figure 3. The final polarizer was then gold plated, as shown in Figure 3.



Figure 3. Electroformed 100 mm long polarizer with gold plating (AM EF 100 mm).

2.2. Stereolithography and Electroless Plating

The 100 mm polarizer was sent to the aerospace company, Swissto12, for printing [24]. Swissto12 uses a combination of additive manufacturing processes and patented coating methods to create state-of-the-art radio frequency devices. The device was first printed with SLA, which utilizes a technique called photopolymerization, where a resin activated by ultraviolet (UV) lasers builds the component layer by layer. The entire structure is then covered in a conductive layer using electroless plating [27]. Multiple polarizers were manufactured by Swissto12, as follows: two proprietary-plated polymer 100 mm polarizer with flanges on each end (AM Polymer 100 mm), as shown in Figure 4, and two proprietary-plated polymer 60 mm polarizer with flanges on each end (AM Polymer 60 mm), as shown in Figure 5a.



Figure 4. Additively manufactured polymer 100 mm polarizer from Swissto12 (AM Polymer 100 mm).

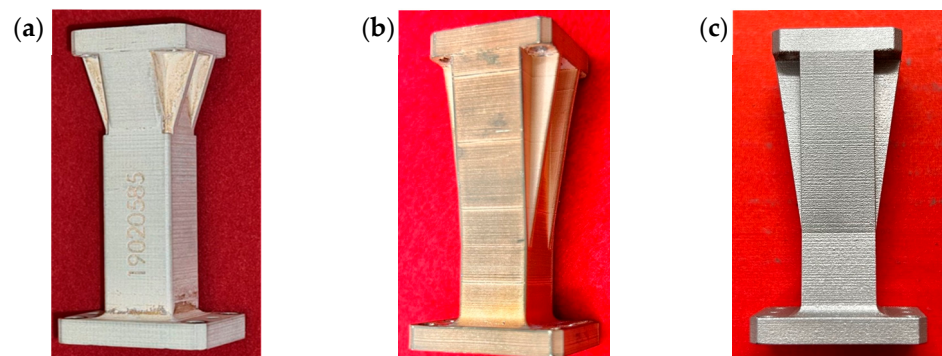


Figure 5. Additively manufactured 60 mm polarizers: (a) AM Polymer 60 mm, (b) AM Cu 60 mm, and (c) AM Al 60 mm.

2.3. Bound Metal Deposition

Through the University of South Australia, a collaboration with the Industry 4.0 Testlab was developed [25]. The Desktop Metal Studio System machine uses BMD to print in layers by extruding copper-filled thermoplastic rods with a 250-micron nozzle. Two 60 mm polarizers (AM Cu 60 mm) were printed within the same batch, as shown in Figure 5b. They were printed in the z-direction, with rectangular ports on the base. This ensured there was symmetry about the septum and reduced possible printing errors due to overhangs. Once these polarizers were printed, they were put through a bath to wash off possible plastic residue before being placed in a furnace. They then went through a sintering cycle, of up to 1300 °C, to further eliminate possible plastic residue, and solidify the printed layers, minimizing the possible stresses within each device. The polarizers were printed with 100% infill, meaning that they were printed in solid copper with no specially designed gaps to reduce material usage.

2.4. Selective Laser Melting

The final polarizers were produced through the Swedish additive manufacturing company Northern Waves (NW) [26]. This company produced two polarizers using Selective Laser Melting, a powder-bed fusion technique, in aluminum alloy (AlSi10 Mg). The polarizers were sandblasted after printing to ensure the smoothest surface possible. The polarizer obtained from NW (AM Al 60 mm) is displayed in Figure 5c.

3. Simulated and Measured Performance

This section explains the details of the CST model for both individual polarizers and back-to-back pairs, along with the measurement setup. The simulated S-parameters and axial ratio results for both configurations are compared with the measured results from the five different manufacturing methods.

3.1. S-Parameters

The 60 mm polarizers were modeled in CST using the 3D CAD models as supplied by the manufacturers to ensure the closest match between measurements and simulations. The CST analysis was performed using two different lossy metals for the polarizer material. The conductivity values used were derived from the measurements outlined in Section 4 of this paper and approximate the conductive and surface roughness losses expected for the BMD and SLM printed polarizers. The S-parameters were measured with CSIRO's 4 port Keysight N5225B Precision Network Analyzer (PNA).

The polarizers were measured in several configurations to ensure we obtained the relevant performance metrics. This included the following: a back-to-back measurement of polarizer pairs produced from each manufacturing method (Figure 6); a measurement of each polarizer with the circular waveguide port short circuited; and a measurement of each polarizer with the circular waveguide port open-circuited, which we call radiating. For the short-circuited measurements, we used a calibration standard shorting plate on the circular waveguide flange. For the open-circuited measurements, we used a custom-made box filled with absorbing material to ensure there were no external interactions affecting the measurements.

Each pair of polarizers was connected back-to-back (Figure 7) to the same four-port PNA with a custom adapter used to separate the rectangular waveguide ports, as shown in Figure 8 with the AM EF 100 mm polarizers. The results of the reflection and transmission coefficients and isolation are shown in Figures 9–12. These results have only been modified to subtract the effects of the adapters from the transmission coefficient polarizer measurements to ensure an accurate representation. The adapter effects were calculated

by measuring the s-parameters of only the adapters across the entire frequency range of interest. This ensured that the frequency-dependent adapter losses were accounted for in the removal calculations. The waveguide adapters were manufactured by Northern Waves using the same printing process as the polarizers. The adapters were measured by themselves using the same process as used for the polarizers, and the insertion loss of the adapters was removed from the polarizer measurements presented here. The reflection coefficient of the polarizers shown here is as measured with the adapters, and we believe this is acceptable because the matching of the adapters is better than that of the polarizers.

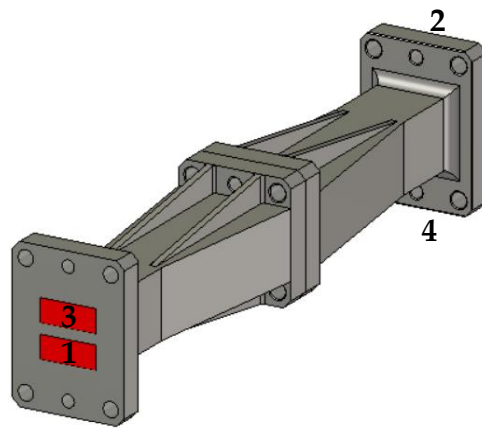


Figure 6. Position of four defined rectangular ports for each polarizer in ‘through’ back-to-back formation in CST Studio Suite.

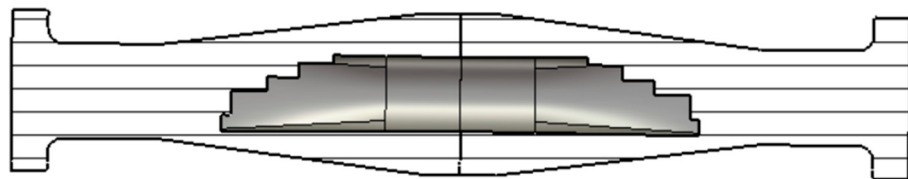


Figure 7. Orientation of internal stepped septum for each polarizer in ‘through’ back-to-back formation in CST Studio Suite.

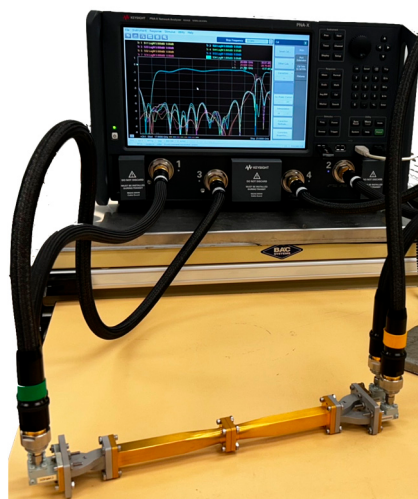


Figure 8. Back-to-back ‘through’ setup with network analyzer for AM EF 100 mm polarizers.

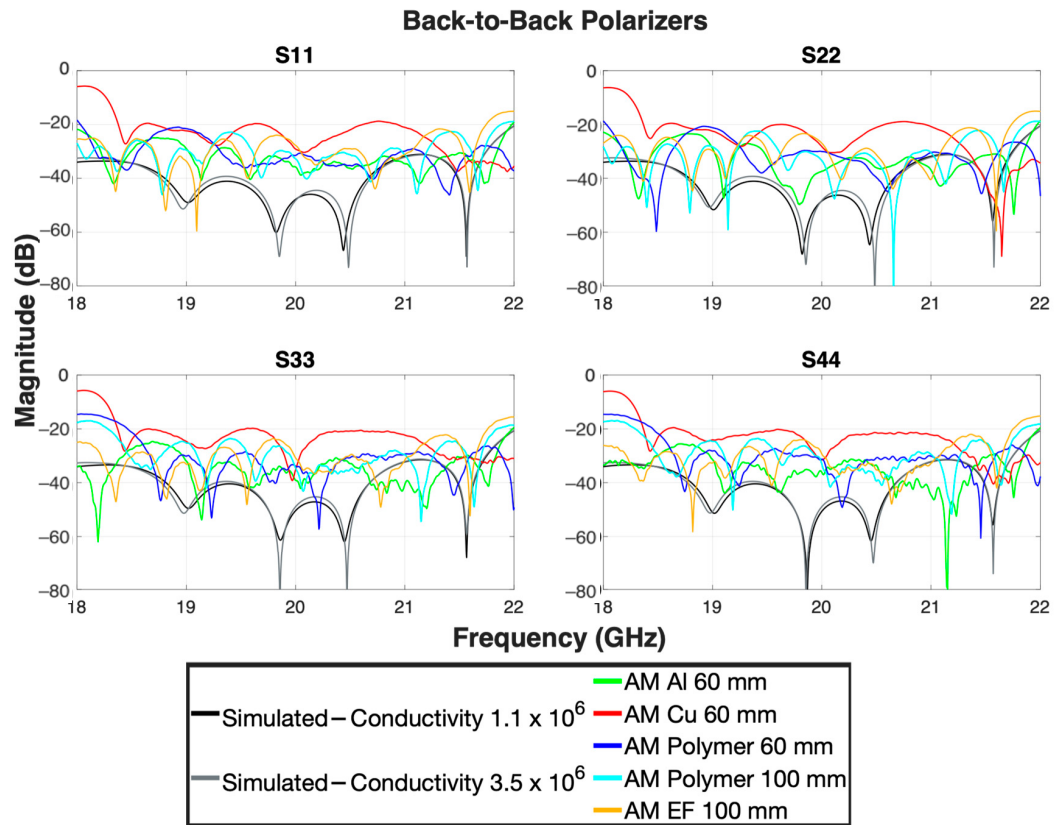


Figure 9. Back-to-back reflection coefficients for multiple pairs of polarizers.

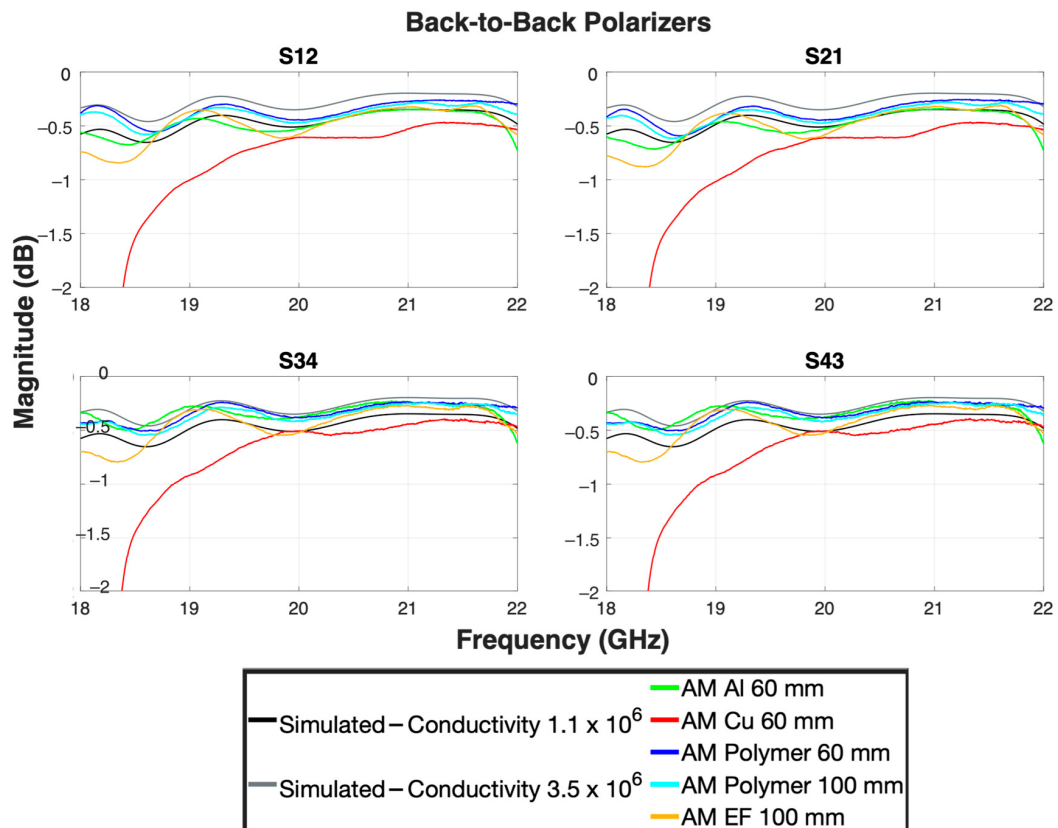


Figure 10. Back-to-back transmission coefficients for multiple pairs of polarizers.

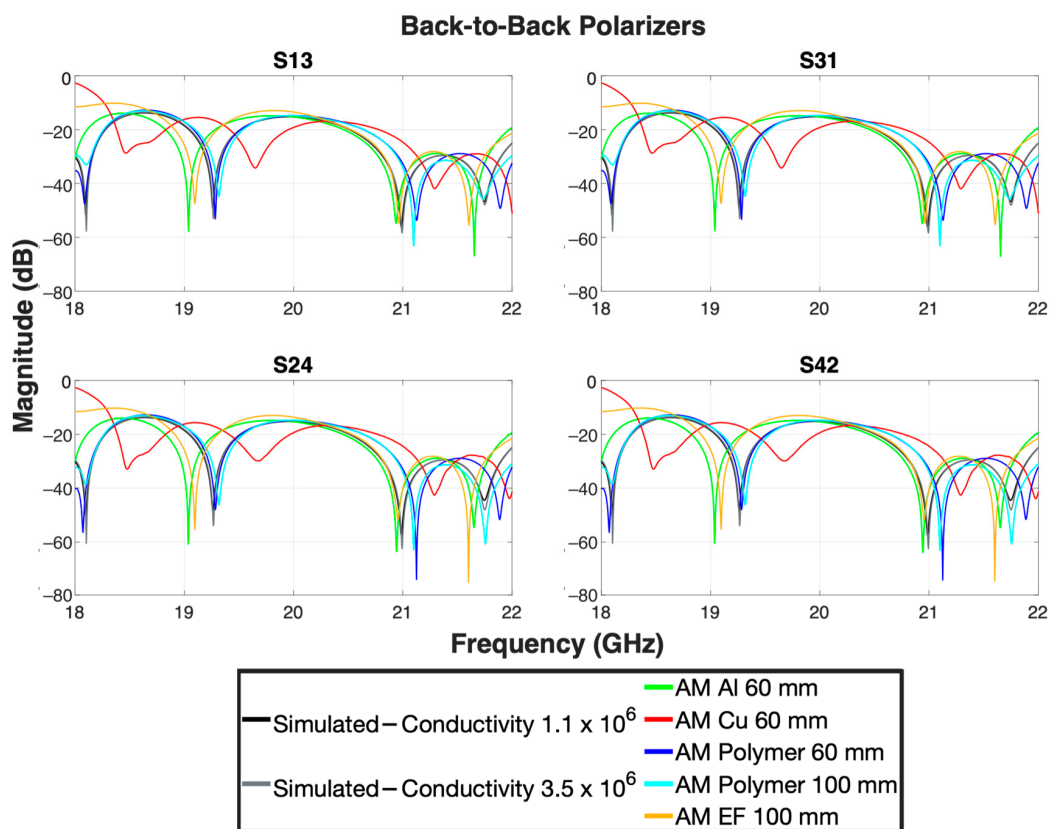


Figure 11. Back-to-back isolation for multiple pairs of polarizers.

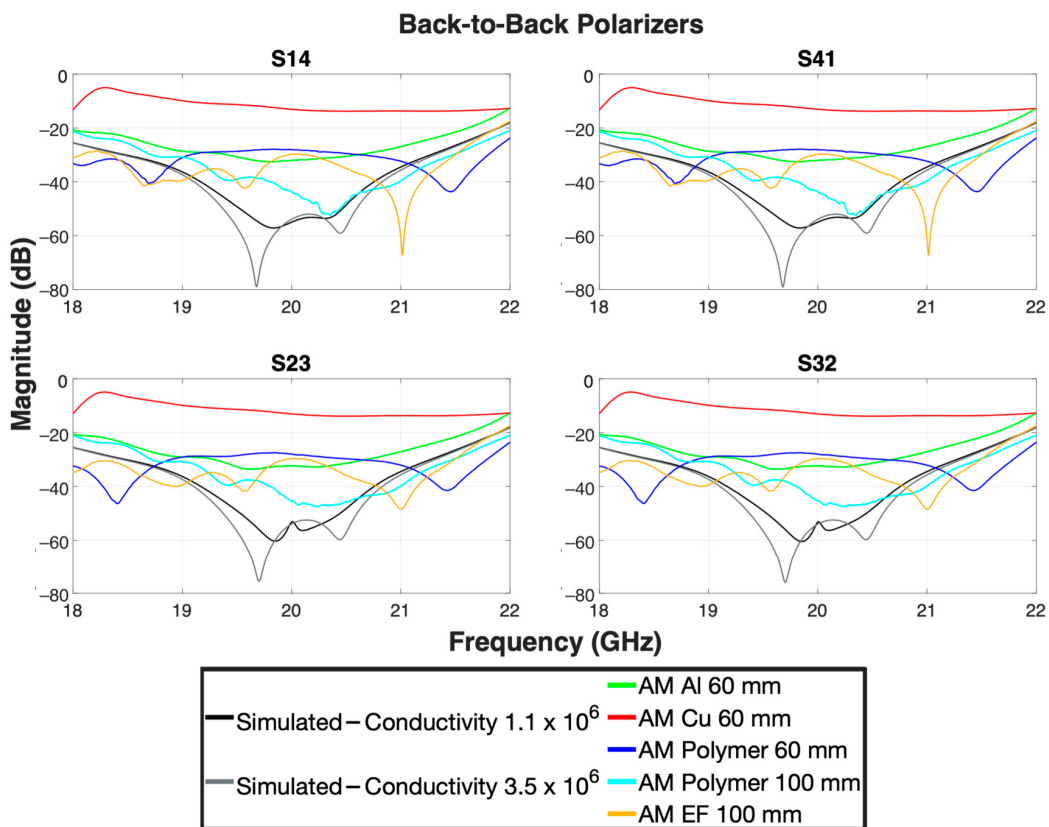


Figure 12. Back-to-back 'through' transmission coefficients for multiple pairs of polarizers.

Figure 9 shows the input reflection coefficient of each of the four rectangular waveguide ports for each of the back-to-back polarizer pairs compared with the simulated results from CST for the same polarizer configuration. Similar characteristics are observed across most AM methods except for the AM Cu polarizers. The reflection coefficients measured in this way should be accurate provided the devices being measured are well matched. This can be checked by comparing the reflection coefficients with the radiating polarizer measurements shown below.

The transmission coefficients for the various back-to-back polarizers shown in Figure 10 are a measurement of the through signal path from a rectangular waveguide input port on one polarizer to the corresponding rectangular waveguide output port on the second polarizer after linear-to-circular and circular-to-linear conversion. If we assume the two polarizers are identical, the insertion loss of a single polarizer will be approximately half of the magnitude of this measured transmission coefficient. The Al, Polymer, and EF polarizers all have an excellent insertion loss across the frequency band of 18–22 GHz of less than 0.5 dB through both polarizers. The Cu polarizer does not perform as well from 18 to 20 GHz with an insertion loss ranging from less than 2 dB to 0.5 dB across the same frequency range.

The S-parameters shown in Figures 11 and 12 are measures of the isolation or cross-polarization of the polarizer. Figure 11 represents the reflected cross-polarization component through both polarizers in both directions. This shows quite close agreement between the simulation and the measurement for all devices except the Cu polarizer. Figure 12 is the cross-polarization component through both polarizers in one direction only. Figures 11 and 12 demonstrate an excellent match between the simulated results and AM Polymer polarizers. Although there are some minor differences with the AM Al polarizers and AM EF 100 mm length polarizers, these devices still show a very good match with the simulated models. Conversely, the AM Cu polarizers have noticeable differences between the measured and simulated results. A possible frequency shift is also observable in these transmission coefficients.

To ensure accuracy with these results, single polarizer radiating measurements were also obtained. The single polarizer setup was the same as the back-to-back setup displayed in Figures 6 and 7, except with only one polarizer's circular port radiating into space. As four-port measurements were previously obtained, only those port definitions will be used to avoid confusion between port numbers, as shown in Figure 6. For the radiating simulations, the circular waveguide did not have a port defined, which ensured the signal input at the rectangular ports simply radiated out of the circular port. A similar setup was used for the single polarizer radiating measurements, where the open circular port of the polarizer simply faced the RF-absorbing material. This absorber ensured there were no external reflections that would affect the measurements. As previously mentioned, two devices were printed to be able to obtain back-to-back measurements, as well as showcase the consistency of AM. As such, for the single polarizer radiating measurements, there are two sets of each polarizer named V1 and V2.

Figures 13 and 14 display the simulated and measured radiating S-parameters for each pair of polarizers for the various manufacturing methods.

Figure 13 is the input reflection coefficient of each of the polarizers, and while there are differences when compared to Figure 9, the results match the simulation well and show the polarizers are well matched. The differences between Figures 9 and 13 can be explained by the different test setups. The radiating setup will introduce an extra mismatch due to the open-circuited circular waveguide. As it is not possible for us to measure the polarizers with a perfectly matched circular waveguide port, by modeling this in CST, we are confident in the performance of the polarizers. Figure 14 shows the isolation of

each of the polarizers, which is a measure of the cross-polarization performance of the polarizer. In this case, it is a measure of the reflected signal in the opposite polarization to the one desired. Good agreement is seen between the measurements and CST. The results in Figure 13 show that both AM Cu 60 mm polarizers printed using BMD, shown in red, are the most dissimilar from the results obtained from other methods of manufacturing.

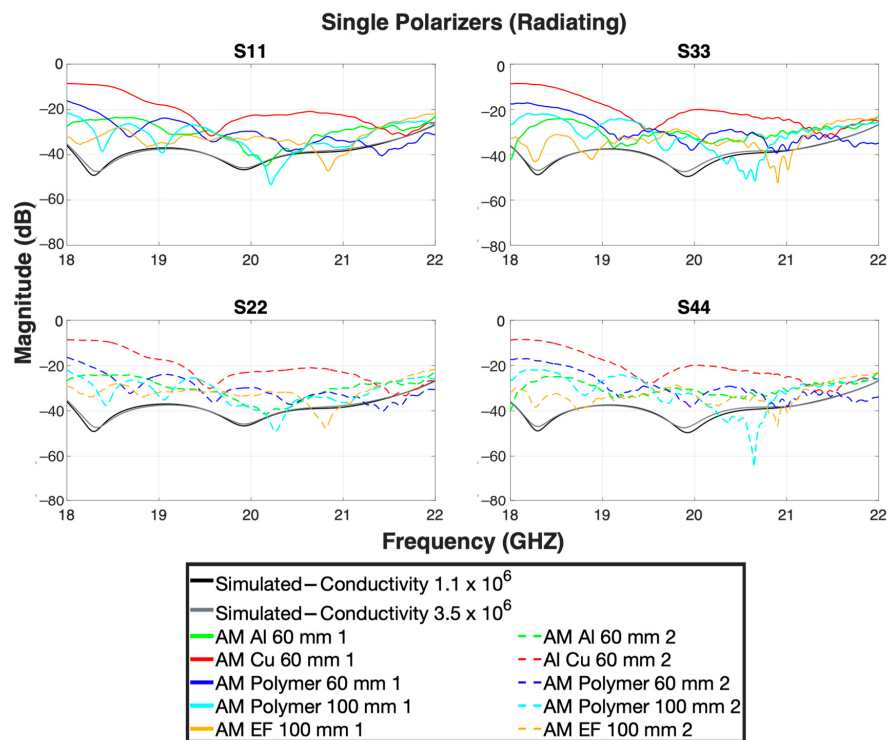


Figure 13. Reflection coefficients of single polarizers with circular port radiating.

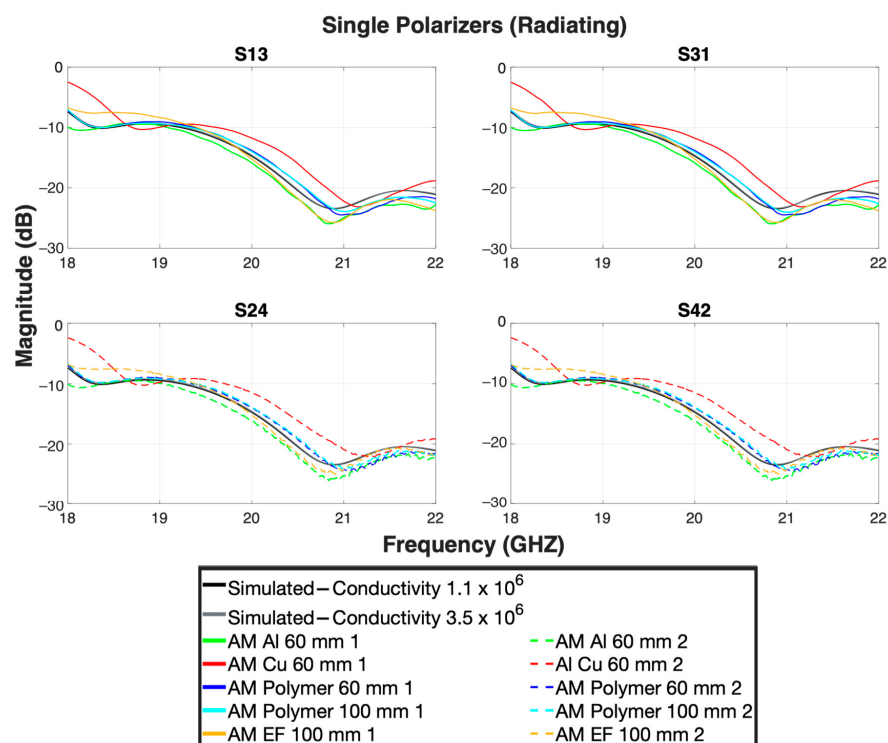


Figure 14. Isolation of single polarizers with circular port radiating.

Figure 15 shows the transmission coefficients of the polarizers when shorted at the circular waveguide port and Figure 16 shows an isolation or cross-polarization measure. The differences between Figures 10 and 15 and, in particular, the reduced ripple observed in Figure 15 show that there are some internal reflections impacting the results of the back-to-back polarizers.

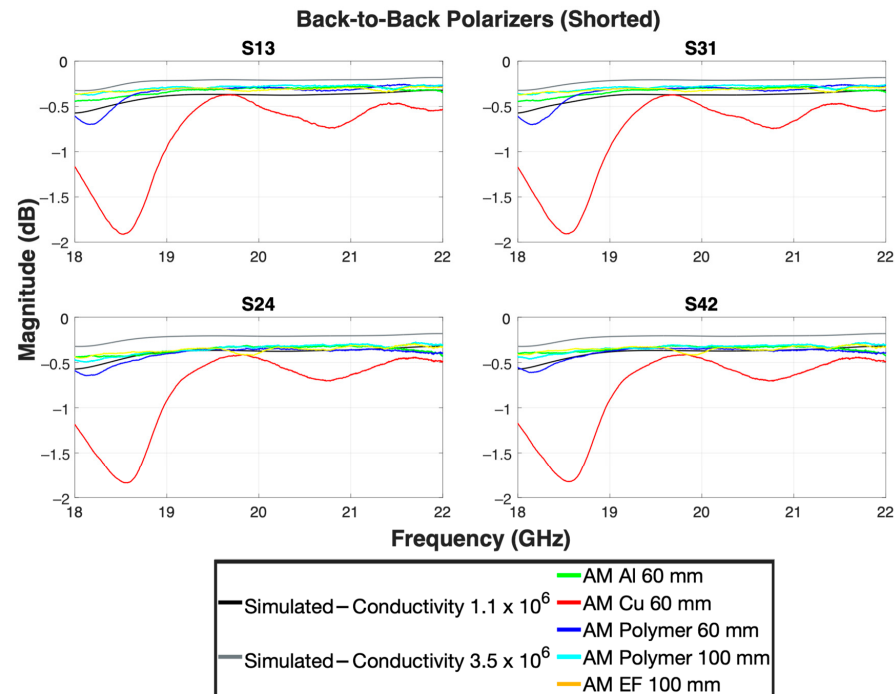


Figure 15. Transmission coefficients of back-to-back polarizers with a short sandwiched between them.

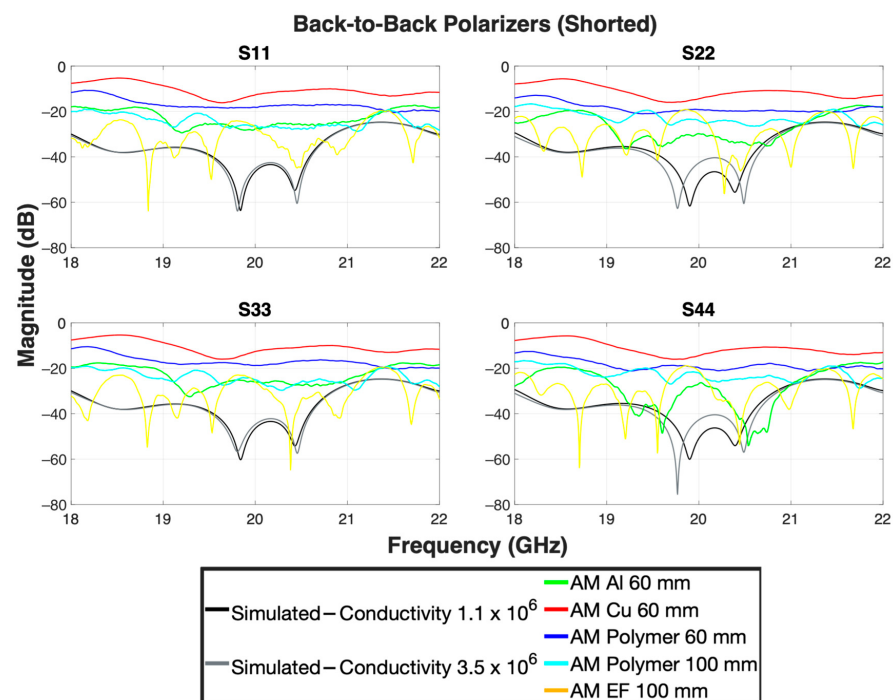


Figure 16. Isolation of back-to-back polarizers with a short sandwiched between them.

Overall, the measured performance of the individual polarizers closely matches the simulated results while also exemplifying the consistency of AM devices. The measured

insertion loss of all AM polarizers except the AM Cu 60 mm is less than 0.2 dB across the 18–22 GHz frequency range. The AM Cu 60 mm polarizer does not perform well across the whole band; however, its insertion loss is around 0.5 dB from 19.5 to 22 GHz. The reflection and isolation performance of the polarizers follow similar patterns. This shows that the Al, polymer and EF polarizers all perform very well, and the Cu polarizer does not perform as well. Section 4 describes the measurement of dimensions and discusses the reasons for these discrepancies.

3.2. Axial Ratio

The axial ratio was measured within CSIRO's farfield anechoic chamber in Marsfield and compared to the simulated results. A linear spinning source was used and both the LHCP and RHCP were measured by undertaking two sets of measurements with each polarizer using both rectangular waveguide ports. The circular polarization was measured through a single rectangular port and by placing a custom ferrite load in the unused rectangular port to reduce cross-polarization.

The first axial ratio plots displayed in Figure 17 show the axial ratio versus the theta angle in degrees, whereas Figure 18 displays the axial ratio versus frequency for both polarizations measured at a theta of 0 degrees. These figures show very good agreement between the measured and simulated AR. The Cu polarizer does not perform as well, which is expected and reflected in the S-parameter measurements. The AR versus theta results are useful only over a small angular range, due to the measurements being undertaken with a waveguide flange on the circular waveguide ports.

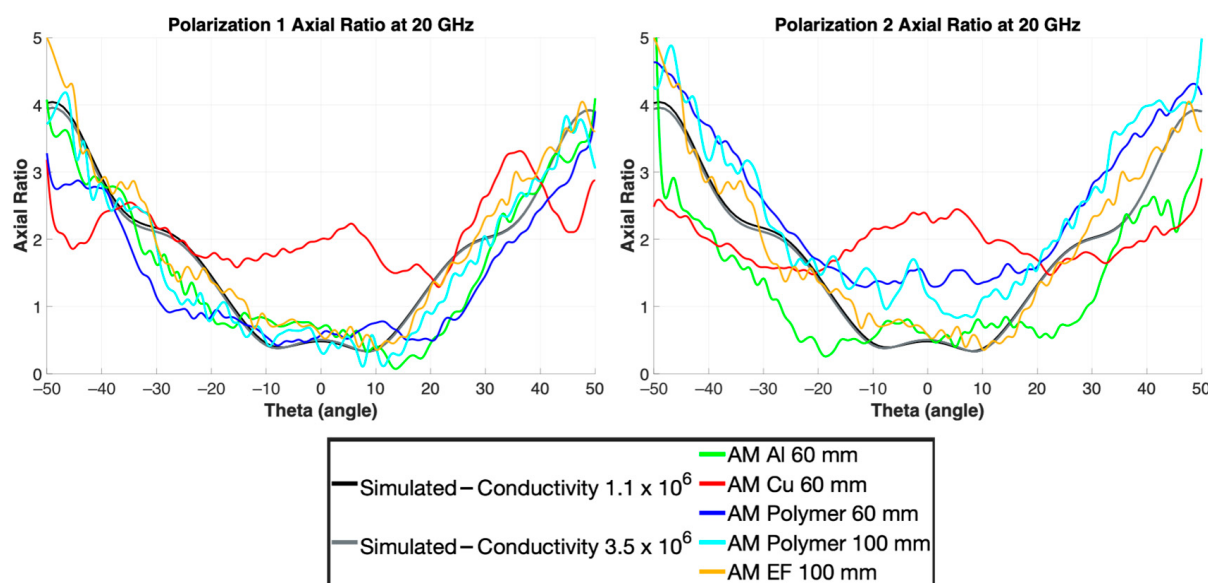


Figure 17. Axial ratio versus theta angle for polarization 1 and polarization 2.

These figures show that, despite the AM Cu 60 mm polarizers not matching the axial ratio of the other polarizers, it is still a reasonable and useable value. This is particularly obvious in Figure 17, where the axial ratio is observed below 3 dB across all angles of theta. Although there is a spike observable around 18.5 GHz, as shown in Figure 18, the rest of the frequency band shows AR less than 3 dB. More consistent results were identified with the aluminum polarizers, especially around the boresight angle, as shown in Figure 17. The aluminum polarizers display an AR of less than 2 dB across the frequency range of interest for this investigation. Such values indicate that the AM Cu 60 mm polarizers, despite not operating at the designed level of performance, can still be used

within a system where a high-performance aspect is not required. This also indicates that the aluminum polarizers operate to a similar level of the traditionally manufactured and higher-cost polarizers.

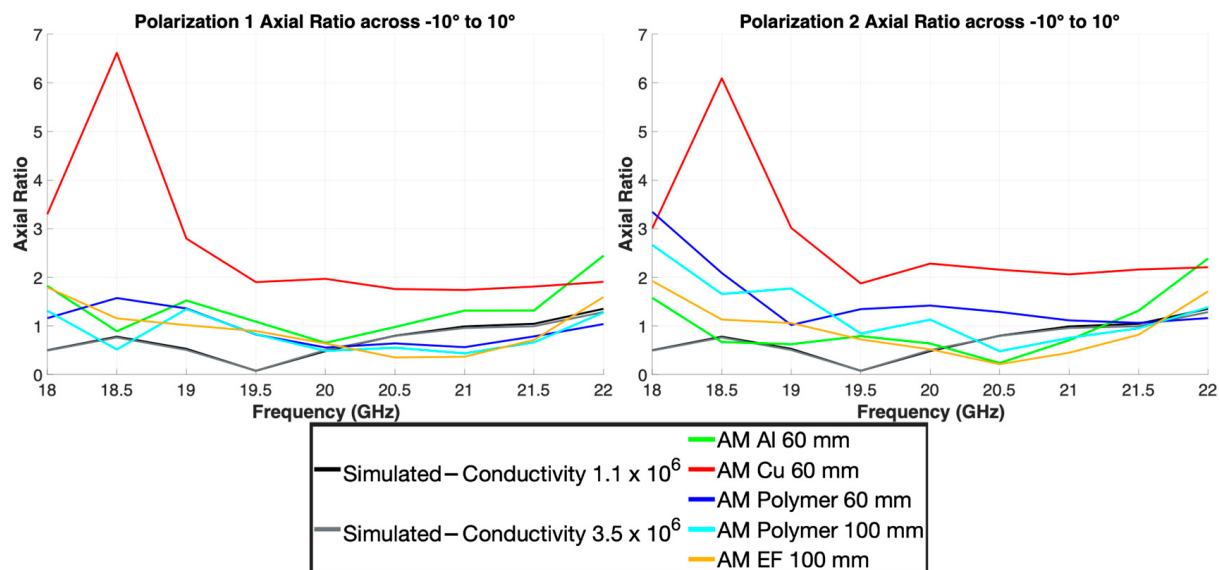


Figure 18. Axial ratio versus frequency for polarization 1 and polarization 2.

Table 1 summarizes the S-parameters and axial ratio values within the specific frequency range under investigation.

Table 1. Summary of measured back-to-back polarizer results from four manufacturers compared with simulation results at 20 GHz.

Polarizers	(dB)										Axial Ratio (Boresight)
	S11	S22	S33	S44	S13, S31	S24, S42	S12, S21	S34, S43	S14, S41	S23, S32	
Simulated-Conductivity 1.1×10^6	−50	−50	−50	−50	−15	−15	−0.5	−0.5	−65	−60	0.25
Simulated-Conductivity 3.5×10^6	−50	−50	−50	−50	−15	−15	−0.25	−0.25	−65	−60	0.25
AM EF 100 mm	−25	−25	−30	−30	−15	−15	−0.5	−0.5	−30	−30	0.5
AM Polymer 60 mm	−30	−25	−35	−30	−15	−15	−0.5	−0.4	−30	−30	0.5
AM Polymer 100 mm	−30	−30	−35	−30	−15	−15	−0.5	−0.4	−45	−45	1
AM Cu 60 mm	−25	−25	−35	−30	−20	−20	−0.75	−0.5	−15	−15	2
AM Al 60 mm	−35	−35	−40	−35	−15	−15	−0.5	−0.4	−30	−30	0.5

4. Analysis of Printed Properties

To complete the characterization of the presented AM methods, a selection of polarizer dimensions were measured and the conductivity and surface characteristics were measured. The printing specifications and quality were examined through conductivity measurements, skin depth calculations, optical microscopy, and scanning electron microscopy (SEM). In the following, the details of the measurement and calculation process are explained and the results are presented. These results were presented at APICAM in 2023 [28].

4.1. Dimensional Measurements

Metrology was undertaken on four of the polarizers to evaluate the dimensional and geometrical accuracy of each of the manufacturing methods. Table 2 summarizes the

dimensions measured and compares these with the design values for each dimension. The circular waveguide diameter and roundness were measured, as well as rectangular waveguide width and height, septum thickness and three of the septum step lengths. The fourth septum step length could not be measured due to the tight step this forms inside the waveguide. Photographs of each of the four polarizers from the septum end and rectangular waveguide end are included in Figures 19–22 to visually illustrate the squareness of the waveguides and septum steps.

Table 2. Summary of dimensional measurements of manufactured polarizers.

Polarizers	Circular Waveguide Diameter (mm)	Circular Waveguide Roundness (mm)	Rectangular Waveguide Width (mm)	Rectangular Waveguide Height (mm)	Septum Thickness (mm)	Septum Step 1 Length (mm)	Septum Step 2 Length (mm)	Septum Step 3 Length (mm)
Simulated-Conductivity 1.1×10^6 and 3.5×10^6	10.00	0.000	10.668	4.318	2.032	4.64	4.30	4.74
AM EF 100 mm	9.99 (−0.01)	0.006	10.638 (−0.030)	4.317 (−0.001)	1.991 (−0.041)	4.64	4.30	4.74
AM Polymer 60 mm	9.99 (−0.01)	0.060	10.704 (+0.036)	4.334 (+0.016)	2.032	4.60 (−0.04)	4.32 (+0.02)	4.72 (−0.02)
AM Cu 60 mm	9.70 (−0.30)	0.130	10.466 (−0.202)	4.216 (−0.102)	2.183 (+0.151)	4.66 (+0.02)	4.24 (−0.06)	4.82 (+0.08)
AM Al 60 mm	10.08 (+0.08)	0.060	10.739 (+0.071)	4.382 (+0.064)	1.981 (−0.051)	4.61 (−0.03)	−4.32 (+0.02)	4.71 (−0.03)

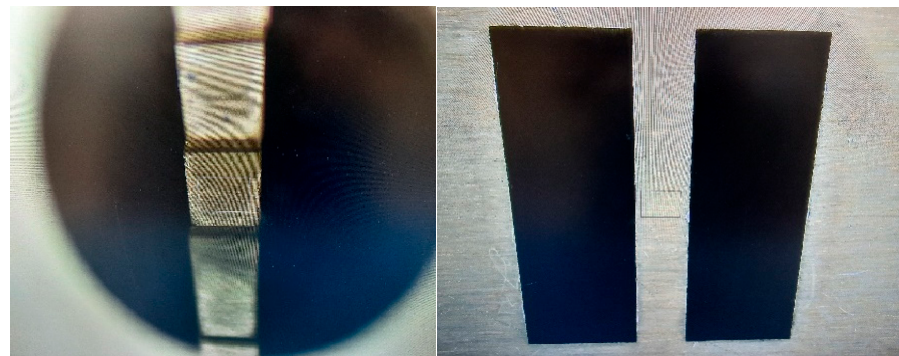


Figure 19. Photograph of AM EF 100 mm septum steps (left) and rectangular waveguide ports (right).

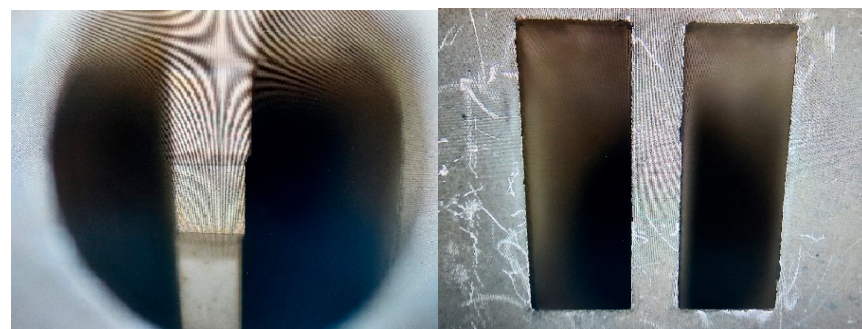


Figure 20. Photograph of AM Polymer 60 mm septum steps (left) and rectangular waveguide ports (right).

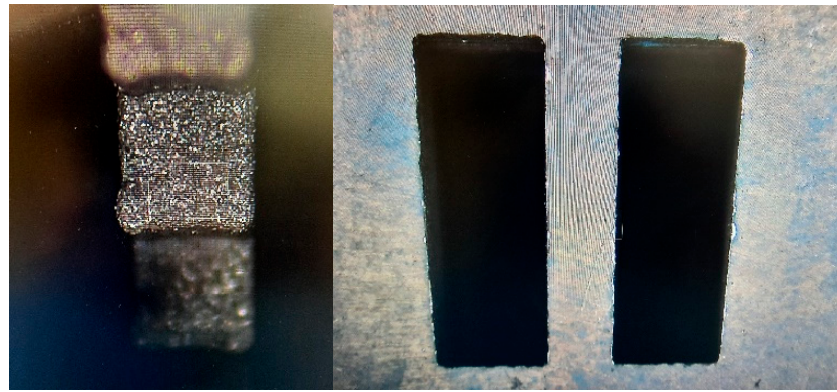


Figure 21. Photograph of AM Cu 60 mm septum steps (**left**) and rectangular waveguide ports (**right**).

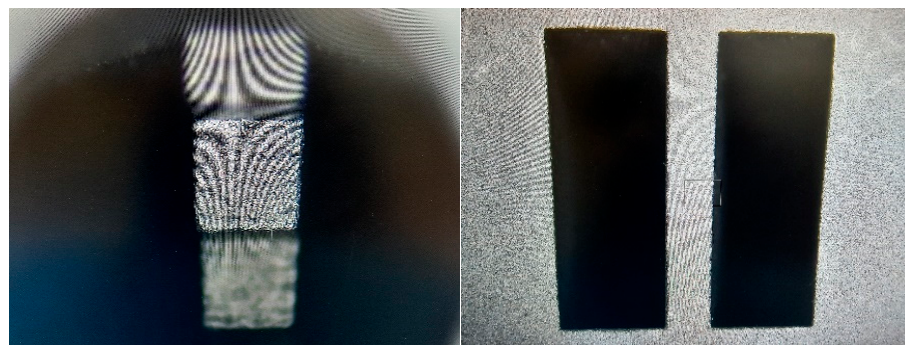


Figure 22. Photograph of AM Al 60 mm septum steps (**left**) and rectangular waveguide ports (**right**).

The AM EF 100 mm polarizer is dimensionally consistent overall with a variation in the septum thickness of -0.041 mm, and has an even surface finish and reasonably clean edges on septum steps and waveguides. The AM Polymer 60 mm polarizer is also dimensionally consistent with slightly greater dimensional variation than AM EF 100 mm, although it has a perfect septum thickness and the sharpest septum faces and edges. The AM Al 60 mm polarizer has uniform surfaces with greater dimensional variation than the AM EF 100 mm and AM Polymer 60 mm and higher surface roughness, which has an impact on measurement accuracy. The AM Cu 60 mm polarizer has a rough surface finish, which makes it difficult to obtain accurate measurements. The external edges and corners are rounded by approximately 0.1–0.2 mm, the circular and rectangular waveguides are undersized by 0.3 and 0.2 mm, respectively, and the circular waveguide is out of round.

4.2. Conductivity Measurements and Skin Depth Calculations

By using the same printing process as that of the AM Cu and AM Al polarizers, 12 disks of 35 mm diameter with 1 mm thickness, and 12 disks of 25 mm diameter with 1 mm thickness were printed. The conductivity of each of these disks was then calculated using the Q-factors of resonant cavities at 10 GHz and 25 GHz. The technique used is outlined in more detail in [28]. This method uses a cylindrical copper cavity, along with a small cylindrical ‘puck’ of a known material, in this case, a magnesium fluoride (MgF₂) puck for the 10 GHz resonator and a lithium fluoride (LiF) puck for the 25 GHz resonator, to obtain the relevant parameters from the material under test.

By placing the metallic disks in a cylindrical copper cavity, we obtained the relevant parameters to calculate the conductivity of the printed copper material. These conductivities are displayed in Table 3 from the 10 GHz resonator and Table 4 from the 25 GHz resonator.

Table 3. Conductivity measurements and skin depths with 10 GHz resonator.

Material	Conductivity (MS/m)	Skin Depth (μm)	Probe Position
Machined Copper	34.75	0.79	At Walls
	35.49	0.78	Half Turn Out
	35.50	0.78	Full Turn Out
BMD Copper	17.88	1.13	At Walls
	18.18	1.10	Half Turn Out
	17.01	1.17	Full Turn Out
Machined Aluminum	21.09	1.01	At Walls
	21.06	1.01	Half Turn Out
	20.34	1.03	Full Turn Out
SLM Aluminum	9.43	1.53	At Walls
	9.40	1.53	Half Turn Out
	9.41	1.53	Full Turn Out

Table 4. Conductivity measurements and skin depths with 25 GHz resonator.

Material	Conductivity (MS/m)	Skin Depth (μm)	Probe Position
Machined Copper	8.43	1.24	At Walls
	8.72	1.21	Half Turn Out
	8.58	1.22	Full Turn Out
BMD Copper	1.18	3.08	At Walls
	1.11	3.18	Half Turn Out
	1.14	3.14	Full Turn Out
Machined Aluminum	7.33	1.24	At Walls
	7.95	1.19	Half Turn Out
	7.93	1.19	Full Turn Out
SLM Aluminum	3.48	1.89	At Walls
	3.60	1.85	Half Turn Out
	3.53	1.87	Full Turn Out

The values of conductivity measured using this method include a component for surface roughness. This was intentional so we can use an estimated conductivity that incorporates conductive and surface roughness losses. The conductivity used for the CST simulations was 1.1 MS/m for the AM Cu 60 mm polarizer and 3.5 MS/m for the AM Al 60 mm polarizer.

4.3. Microscopy

Using James Cook University's Olympus CX31 microscope, we were able to obtain images of the AM Cu disks' surfaces. External lighting was employed as the disks are not transparent. This limited the operation of the microscope as it is intended to be used with relatively transparent materials.

Images were obtained for both the small and large disks at $4\times$ magnification (Figure 23) and $10\times$ magnification (Figure 24). It can be clearly observed in Figure 23 that there is a difference in the printing patterns between the 25 mm and 35 mm disks. The 25 mm disk clearly displays a crosshatch pattern to its layers, whereas the 35 mm disk displays more uniform layering.

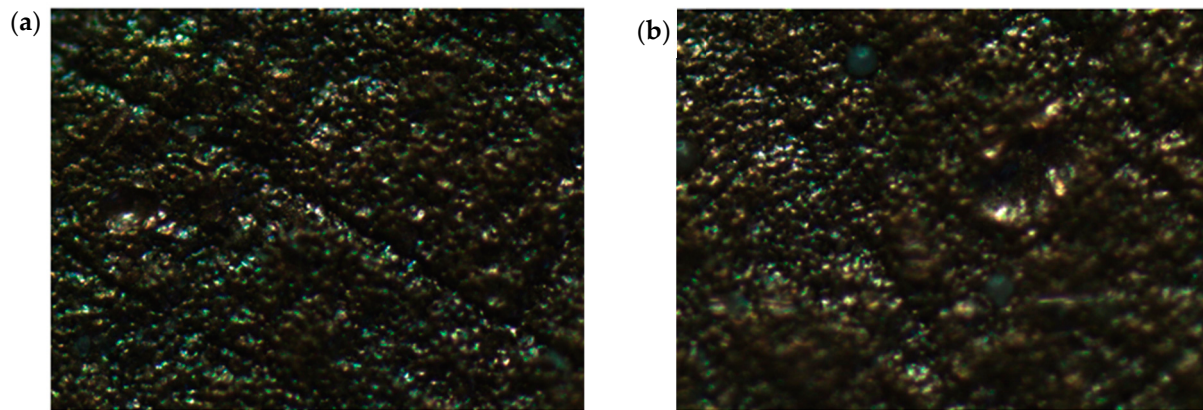


Figure 23. Images at $4\times$ magnification with clear observable printing patterns of both: (a) AM Cu 25 mm diameter disk and (b) AM Cu 35 mm diameter disk.

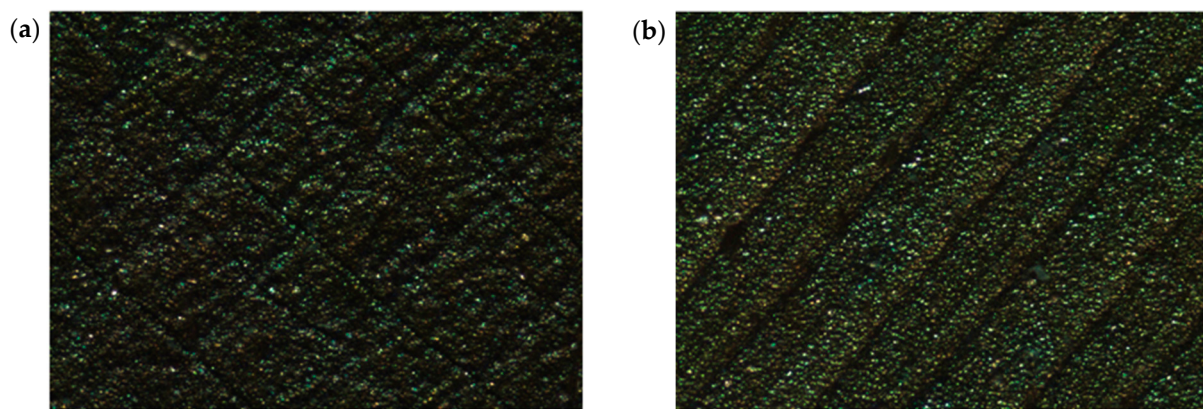


Figure 24. Images at $10\times$ magnification, with possible plastic residue, of both: (a) AM Cu 25 mm diameter disk and (b) AM Cu 35 mm diameter disk.

By further looking at the $10\times$ magnification images in Figure 24, we can see that there is some possible plastic residue left either on the surface or within the layering of the disks. These small bead-like objects could explain some of the variation in the results for the polarizer due to the plastic causing unwanted reflections or refraction of the EM wave. There could also be interruptions to the surface currents in the wall of the device, which can also reduce its efficacy.

However, further understanding of these identified layers and possible plastic residue is required before definitive conclusions can be made.

4.4. Scanning Electron Microscopy

To further investigate the surfaces of the AM Cu disks, scanning electron microscopy (SEM) was undertaken at James Cook University. SEM uses an electron beam to observe the surfaces of small sections of interest. Due to this use of an electron beam, usually, non-conductive pieces are coated in gold to ensure the surface can be observed. However, the AM Cu disks did not require this due to their high conductivity. Both backscatter and secondary imaging were used to compare between the two sizes of disk to properly identify what is plastic residue and what is simply surface debris or cracks.

Firstly, an AM Cu 35 mm disk was placed within the SEM imaging machine, and images were obtained of one side at $25\times$ and $100\times$ magnification, with both backscatter and secondary imaging, as shown in Figures 25 and 26. These images allowed for the clear identification of plastic residue within this single disk side. This was carried out

by comparing the backscatter and secondary images at the same magnification. If the secondary image showed a darker spot, it was checked against the backscatter image to identify if it was also highly contrasted. This is because backscatter imaging assists in identifying chemical characteristics, rather than purely contrast. Therefore, if an area is a possible plastic area in the secondary image, it will appear as a black area in the backscatter image. This, again, is seen in Figure 25, where a definite area of plastic residue was identified.

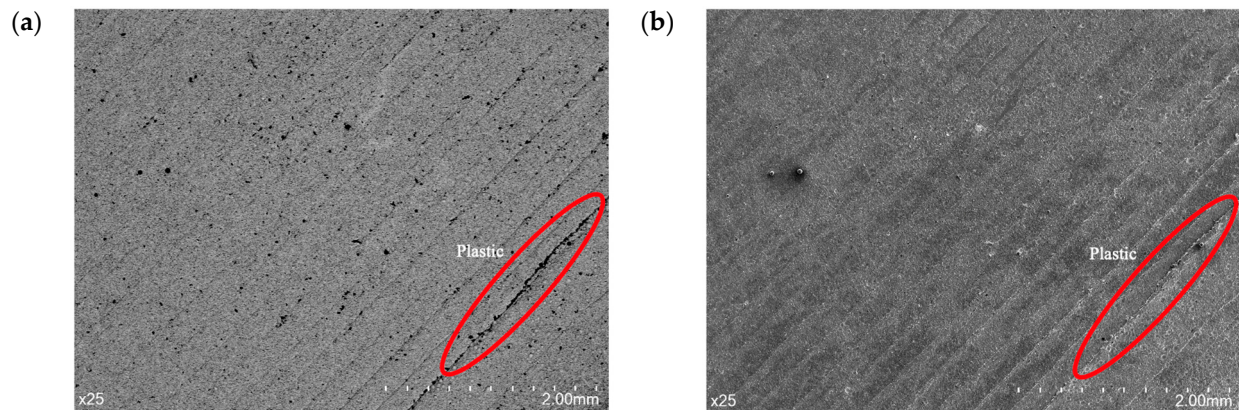


Figure 25. Scanning electron microscopy images at $25\times$ magnification on 35 mm disk: (a) backscatter image identifying plastic within disk and (b) secondary scatter image identifying plastic within disk.

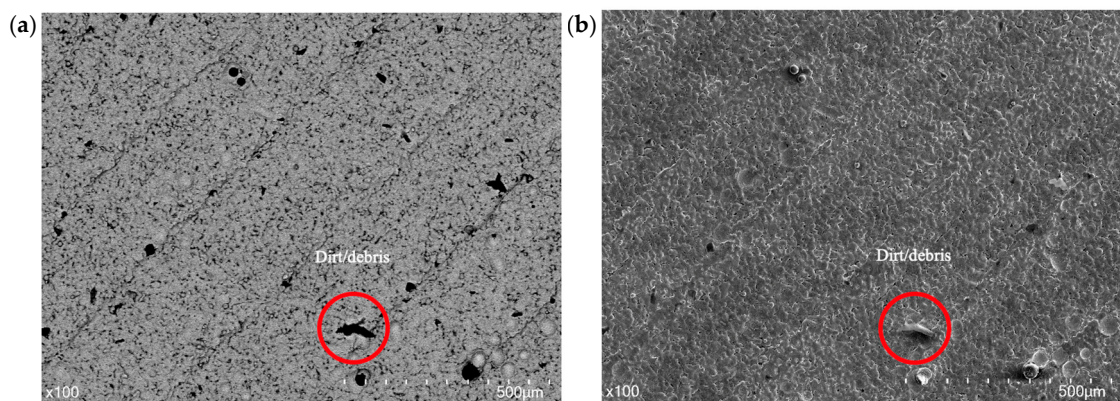


Figure 26. Scanning electron microscopy images at $100\times$ magnification on 35 mm disk: (a) backscatter image identifying dirt/debris on disk and (b) secondary scatter image identifying dirt/debris on disk.

Conversely, if an area looks shadowy in a secondary image and is black in a backscatter image, it is more likely that there will be debris or a crack on the surface of the disk. This is shown in Figure 26, where some debris was identified, most likely due to previous handling.

We observe similarities between our results and those produced by Martín-Iglesias et al. in [7], where they qualitatively compare the surface roughness of the laser beam melting (SLM) and metal binder jetting (MBJ) methods. The authors note that the surface roughness of the MBJ method was 1/5 the roughness observed using SLM [7]. We observe similar smoothness in our bound metal deposition (BMD) disks, as shown in Figures 25 and 26. However, Figure 27 shows how our BMD disks may have less cohesion and bonding between the layers of metal. This may then affect the conductivity of the printed devices that use this method.

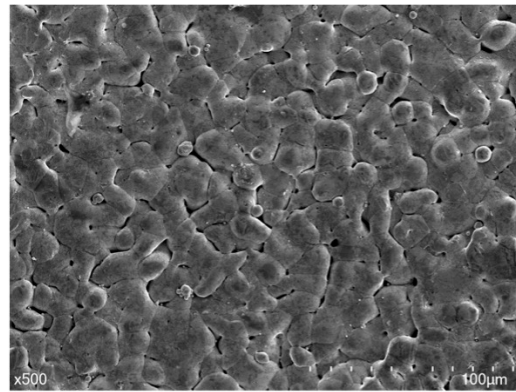


Figure 27. Scanning electron microscopy secondary scatter image at $500\times$ magnification on 35 mm disk identifying gaps between layers.

5. Conclusions

Various AM methods successfully produced stepped-septum polarizers with geometries too intricate for traditional fabrication. The S-parameter and axial ratio measurements revealed distinct performance variations among the AM processes. Conductivity and skin-depth analysis, supported by surface imaging, further highlighted how each manufacturing method influences material behavior. Four manufacturing approaches, machining and electroforming, AM with proprietary coating, BMD, and SLM, were evaluated for accuracy, surface quality, and electrical performance. The electroformed gold polarizer showed the best agreement with the simulation, as expected, and is the most suitable for high-frequency, high-precision applications requiring minimal loss. This method was determined to be the most precise available for the manufacture of this device that was not suited to traditional subtractive methods, and it is also the most complex, costly and slowest of the methods evaluated. The AM polymer process offered good performance with a lower cost and weight, ideal for mid- to high-frequency prototypes, and had the best geometrical tolerances of the methods evaluated. BMD and SLM demonstrated reduced conductivity and higher roughness, making them more appropriate for low- to mid-frequency or cost-driven designs, or when complex geometries are required. Future studies should aim to conduct a comprehensive review and comparison across a wider range of AM methods. Further work should focus on developing designs inherently optimized for AM, rather than adapting conventional geometries, to fully leverage its design freedom. Extending these investigations to higher frequency bands will further broaden the applicability of AM in next-generation microwave and space systems. Another valuable direction for future work would be to perform a more detailed comparison among the individual AM manufacturing methods to identify the underlying causes of their performance differences and provide deeper insight into the specific strengths and limitations of each process.

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Abbreviations

AM	Additive Manufacturing
PBF	Powder Bed Fusion
DED	Directed Energy Deposition
EM	Electromagnetic
DMLS	Direct Metal Laser Sintering
SLA	Stereolithography
BMD	Bound Metal Deposition
UniSA	University of South Australia
NW	Northern Waves
AM EF 100 mm	Electroformed 100 mm Polarizer
UV	Ultraviolet
AM Polymer 100 mm	Swisstol2 Polymer 100 mm Polarizer
AM Polymer 60 mm	Swisstol2 Polymer 60 mm Polarizer
AM Cu 60 mm	University of South Australia Copper 60 mm Polarizer
AM Al 60 mm	Northern Waves Aluminum 60 mm Polarizer
PEC	Perfect Electrical Conductor
PNA	Precision Network Analyzer
AR	Axial Ratio
SEM	Scanning Electron Microscopy
SLM	Selective Laser Melting
MBJ	Metal Binder Jetting

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